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PHENOMENOLOGICAL STUDIES ON QCD AT INTERMEDIATE TEMPERATURES

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ABSTRACT

At finite temperatures a deconfining transition and a chiral symmetry restoring transition are expected to take place. We discuss phenomenological properties in a world where one of these transitions has occurred. We identify clear signals for a state which appears at such intermediate temperatures. We show that very light baryons, which appear when the deconfining transition occurs at a higher temperature than that for the chiral symmetry restoring transition, can account for the "Centauro" events.

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Recently much theoretical work has been done on quantum chromodynamics (QCD) at finite temperatures. Analytic investigations [1] as well as Monte Carlo studies [2,3] reveal interesting properties of the system: liberation of quarks and restoration of chiral symmetry at temperatures much higher than the QCD scale parameter Λ. A new phase possessing these properties also appears in a system which has a very high baryon number density [1,3]. These facts indicate the existence of a deconfining phase transition and a chiral symmetry restoring phase transition *).

Now we have an important question on the relation between the deconfining critical temperature T_d and the chiral symmetry restoring critical temperature T_c. Is T_d greater than, equal to or smaller than T_c [5,6] ? Monte Carlo study on a lattice shows that T_c is nearly equal to T_d [3]. In this study, however, inner quark loops are completely neglected. Since light quark loops are considered to have an important effect on chiral symmetry, we can not rule out the two other possibilities at present. In this note we discuss characteristic properties in all cases: $T_d < T_c$, $T_d > T_c$ and $T_d = T_c$. We also discuss possible signals which would be observed in heavy ion collisions, provided that they realize a thermal equilibrium.

First consider the case where T_c is greater than T_d. Although no proof exists so far, this case seems reasonable theoretically because

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*) It has been suggested that the theory with light fermions might undergo no deconfining phase transition. See Ref. [4].

the force which causes chiral symmetry breakdown is believed to have shorter range than the confining force [5]. When $T_d < T < T_c$, quarks and gluons are liberated and quarks have effective masses, while pions exist as Nambu-Goldstone bosons due to the breakdown of chiral symmetry. So this state can be considered to consist of massless gluons, massless pions and massive quarks.

Let us estimate the effective quark mass in such a state. To do so, we assume that physical quantities have a universal temperature dependence. Then, using Monte Carlo data on $<\bar{\psi}\psi>$ [3], we can get the effective quark mass m(T) at $T \sim 200$ MeV;

$$m(T) = m(0) \cdot [<\bar{\psi}\psi>(T)/<\bar{\psi}\psi>(0)]^{1/3} \sim 280 \text{ MeV}, \quad (1)$$

where we used that $m(0) \sim 300$ MeV. Under the same assumption, pion mass at $T \sim 200$ MeV becomes ~ 130 MeV. Note that the first-order nature of the transition [2,3,6] is essential to these results; if the transition were of second order, $<\bar{\psi}\psi>$ would have been much smaller at this tempetrature. It is reasonable, therefore, to neglect quark degrees of freedom at such T and describe the state as an ideal gas state of gluons and pions. We will refer to this state as a gluon-pion state hereafter.

What signals will be observed for a gluon-pion state in heavy ion collisions ? To answer this question we compare the energy density of this state with the evergy density of a state where pions are the only ingredients of an ideal gas (which we will call a pion state). The enerty density ε_{gp} of the gluon-pion state is, in the ideal gas approximation,

$$\epsilon_{gp} = (\pi^2/30) \cdot T^4 \cdot (16+3) + B \tag{2}$$

where B is the bag pressure which is estimated $\sim$ (200 MeV)^4 [1]. For simplicity, we neglected contributions from the chemical potential. The first term in the parentheses in eq. (2) is the contribution from gluons and the second term from pions. Since gluons carry a large amount of energy in this state, photon radiation in a gluon-pion state will be suppressed compared with that in a pion state, whose energy density ϵ_p is given by

$$\epsilon_p = (\pi^2/30) \cdot T^4 \cdot 3. \tag{3}$$

This means that the emission of virtual photons, which manifest themselves in lepton pairs, will be suppressed in a gluon-pion state as well as real ones. Thus we come to an idea that a gluon-pion state might be observed by a drastic reduction in the lepton pair production rate. Let us estimate this reduction rate, following the discussion by Domokos and Goldman [7]. They showed that the lepton pair production rate dN/dM^2 is proportional to R^4, where M and R denote an invariant mass of a lepton pair and an initial radius respectively, while energy density is proportional to R^{-6}. Therefore lepton pair production rates in the states under consideration are in the ratio of

$$dN/dM^2(\text{gluon-pion state}) \; / \; dN/dM^2(\text{pion state})$$

$$= \{[(\pi^2/30) \cdot T^4 \cdot (16+3) + B] \; / \; [(\pi^2/30) \cdot T^4 \cdot 3]\}^{-2/3} \tag{4}$$

whose value at $T \sim 200$ MeV is ~ 0.26*). This shows us that we can discriminate a gluon-pion state from a pion state very clearly. It should be noted, however, that the M^2 dependence of the distribution is qualitatively same in both states.

Another phenomenon, which is more interesting but more speculative, is expected when the system cools down from the gluon-pion state to the pion state. In the critical region $T \sim T_d$, the system has much chance to produce gluonia as unstable particles because of its excessive gluon degrees of freedom. This interesting possibility will be discussed in detail elsewhere.

Next we will discuss the case $T_d > T_c$. In this case we have a world, at temperatures T between T_c and T_d, where chiral symmetry persists and quarks are confined. Since Nambu-Goldstone bosons never appear in this world, pions will be massive even if u and d quark masses are neglected. Then, pions and rho mesons have masses of the same order here, because they both consist of the constituent quarks with masses of ~ 300 MeV.

We find an interesting fact that there exist very light baryons in this world. This can be confirmed by an argument analogous to 'tHooft's discussion on preons [8]. In his work 'tHooft investigated a confining theory which has a chiral symmetry that is not spontaneously broken. He determined, using the anomaly constraints, a spectrum of massless

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*) We can know the value of T from, for example, the M^2 dependence of the lepton pair production rate.

composite fermions. His argument applies to our light quarks, u and d, at $T_c < T < T_d$ because the anomaly constraint equations remain valid at finite temperatures [9]; the anomaly coefficients are unchanged at finite temperatures since they result from a property at short distances. Thus we see proton and neutron become almost massless. Strange baryons remain massive, on the other hand, because the s quark mass is too large to be neglected. Baryons with higher spins are also massive, since the argument at zero temperature which inhibits the existence of massless baryons with higher spins applies to the finite temperature case without difficulity [10]. Therefore we come to the conclusion that only the proton and neutron can exist as nearly massless particles when $T_c < T < T_d$.

Let us comment on some phenomenological properties of this state. In heavy ion collisions, if the state with T between T_c and T_d is realized, we will observe an excess of baryons and antibaryons in the central region. Here we present a crude estimate for the multiplicity of baryons and antibaryons in the central region. In our picture baryons are nearly massless within a fireball, where the thermal equilibrium is realized, while they have a mass M_B = 940 MeV outside the fireball. We suppose that baryons and antibaryons move freely in a square well potential with depth M_B. Since only those baryons or antibaryons that have enough kinetic energy to overcome the potential can come out from the fireball, the ratio of the escaped baryons and antibaryons, R_B, is given by

$$R_B = \int_{|k|>M_B} d^3k/(2\pi)^3 \ (1 + e^{\beta k})^{-1} \ / \int d^3k/(2\pi)^3 \ (1 + e^{\beta k})^{-1} \tag{5}$$

From eq. (5) we get $R_B = 0.17$ for $T = \beta^{-1} = 200$ MeV. Therefore, if light baryons and antibaryons have the same particle density as that estimated for pions [11], we expect the multiplicity per rapidity is

$$dN_{B+\bar{B}} / dy = 20 \cdot A^{2/3} \ [1\mathrm{fm}/d_o]^2 \ R_B \ , \tag{6}$$

where A denotes the baryon number and d_o^2 the effective elementary area whose value is $(0.3)^2 \sim (1.0)^2$ fm^2. For the uranium nuclear collisions, for example, eq. (6) gives

$$dN_{B+\bar{B}} / dy = 130 \cdot [1\mathrm{fm}/d_o]^2 \ , \tag{7}$$

which is four or more times larger than that estimated for hadron-hadron collisions [12]. Thus we see that those baryons and antibaryons will be detectable in heavy ion collision experiments. Note that R_B in eq. (6) might be underestimated, because we neglected the contribution from baryons and antibaryons with less energy than M_B, which might be able to escape from the fireball by obtaining some energy from its surface.

In cosmic ray experiments, massless baryon state might give a reasonable explanation for the anomalous event known as "Centauro" [13]. Consider a state which has finite baryon number density ρ. Two critical baryon number densities ρ_c and ρ_d exist, corresponding to the chiral and deconfining transitions respectively. Massless baryon state will be realized at ρ between ρ_c and ρ_d. (Note that ρ_d will be greater than ρ_c because $T_d > T_c$ in this case.) In this range of ρ, it would be possible that $d\varepsilon/d\rho$, where ε is the energy density, is smaller than the nucleon mass*). This suggests the existence of globs of matter stable or metastable against nucleon emissions [14]. Phenomenological studies presented in Ref. [14] indicate that such globs are possible origins for the "Centauro" event. Detailed studies on this subject will be made in a forthcoming paper.

Finally, we will make a few remarks on the case $T_d = T_c$. In this case we can not expect any characteristic phenomena such as the reduction of lepton pair production, gluonia production or baryon excess discussed above. Experimental rejections of these phenomena, therefore, will give evidences to the equality of T_d and T_c.

In this note we discussed characteristic properties of the states with temperatures between T_c and T_d. In order to confront our results with the experiments in a quantitative manner, we need knowledge of the time evolution of the system. For this purpose Landau's hydrodynamics model has been frequently used [11,15]. Unfortunately it is difficult to include effect of a phase transition into this model. To develop our discussion, therefore, we should study a non-equilibrium field theory. In the time evolution described by such a theory, $|T_c - T_d|$ will be very important.

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*) This can be demonstrated using an ideal gas approximation.

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